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Characteristics of Manual Palpation to Localize Hard Nodules in Soft Tissues

Jelizaveta Konstantinova, Min Li, Gautam Mehra, Prokar Dasgupta, Kaspar Althoefer, *Member, IEEE,* and Thrishantha Nanayakkara, *Member, IEEE*

***Abstract*— Improving the effectiveness of artificial tactile sensors for soft tissue examination and tumor localization is a pressing need in robot-assisted minimally invasive surgery. Despite the availability of tactile probes, guidelines for optimal examination behaviors that best exploit soft tissue properties are not available as yet. Simulations on soft-tissue palpation show that particular stress-velocity patterns of probing lead to constructive dynamic interactions between the probe and the tissue to localize hard nodules. However, there has been no methodical validation of such probing behavioral hypotheses using human participants so far. In this study, we use simulation studies to establish open hypotheses on the interaction and influence of relevant behavioral palpation variables, such as finger velocity and trajectory, force exerted by fingers on the accuracy of detection of embedded nodules. We test them by analyzing palpation strategies used by humans to detect hard nodules inside silicone phantoms and ex-vivo porcine organs. Our findings allow us, for the first time, to derive palpation behavior guidelines suitable for the design of controllers of palpation robots.**

***Index Terms*— Minimally Invasive Surgery, Medical Robotics, Palpation, Tactile sensors**

I. Introduction

THE realization of artificial tactile feedback is an important and desired technical feature for various surgical systems. It is already an established fact, that the presence of tactile feedback would increase the effectiveness of robot-assisted minimally invasive surgery (RMIS) and lead to better clinical outcomes [1–3]. In order to implement tactile sensing for this type of procedure, researchers have developed a range of sensing devices [4–6]. In particular, attention is paid to develop probing devices, to scan the surface of soft tissue and to identify the presence of malignant or benign formations [7–9]. Traditional open surgery allows direct access to organs, and therefore the possibility to palpate an organ. Palpation during RMIS is considered desirable, but can be only achieved indirectly through an appropriately programmed robotic tool that can be deployed via a small opening in the abdomen. The implementation of robot-based organ palpation is further complicated due to the nonlinear behavior of soft tissues as well as the uncertainties of the environment. The variability of tactile information should be reduced to a minimum through optimal design of the probing devices and by choosing the most appropriate probing behaviors, given the medical context (such as specific organ or type of the disease). This paper focuses on studying effective ways of soft tissue tactile examination; the detected strategies and behaviors allow the detection of lumps in organs with higher accuracy.

There can be several alternative ways to approach this question. One can perform in-vivo or ex-vivo studies on human organs [10], [11]. However the exact location of a tumor can be unknown and, thus, the effectiveness of the examination cannot be evaluated. Another approach is to use mathematical simulations to understand the responses of soft tissue [12], [13]. However, such models are often very simplified and do not correspond to real surgical conditions. Therefore, in order to understand the effectiveness of a soft tissue examination approach, we suggest that one should study how it is done by humans using their hands to palpate soft tissue embedded with artificial tumors. This paper studies various aspects of manual palpation, which, once understood, will lead to performing a more accurate and effective examination of soft tissue organs in-vivo.

Manual palpation of soft tissue is a technique making use of tactile sensation – a technique commonly applied to examine soft tissue during open surgery. The palpation movements and strategies are specific to the body area being examined. For instance, in prostate examination, a global organ palpation is carried out first; then an area of interest (e.g. near a found abnormality) is focused on and examination movements, such as tapping, vibration and sliding are applied locally [14]. It is reported in the literature that the method of physical examination of soft tissue is not standardized and may vary depending on the physician's preferences [15]. During one single examination, various techniques (such as circular movements and tissue rolling between finger) are usually applied [14], [16]. It is noted that the effectiveness of manual palpation to detect lumps and other abnormalities is limited by the physical abilities of human tactile sensation.

The existing palpation studies can be divided into two

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J. Konstantinova, M. Li, G. Mehra, K. Althoefer and T. Nanayakkara are with the Department of Informatics, King's College London, Strand, London WC2R 2LS, U.K. (e-mail: {jelizaveta.zirjakova; min.m.li; gautam.mehra; kaspar.althoefer; thrish.antha }@kcl.ac.uk).

P. Dasgupta is with the MRC Centre for Transplantation, DTIMB and NIHR BRC, King's College London, Guy's Hospital, London SE1 9RT, U.K. (e-mail: prokarurol@gmail.com).

groups. The first set of works is concentrated on the comparison of the performance of human tactile sensation with existing tactile devices [17], [18]. In that case, the main focus is on the evaluation of sensitivity and accuracy of a particular tactile device. Other researchers discuss clinical studies describing methods of manual soft-tissue examination for different organs, such as patterns of movement and recommendations for manual palpation procedure [19], [20]. These studies evaluate the accuracy and tumor detection rates for manual palpation, but are not providing general physical quantifications for different movement types during palpation. A study [21] discusses the importance of force and velocity during virtual palpation simulation via a haptic device. Furthermore, this work highlights the dependence of the magnitude of the finger velocity during palpation on the stiffness of the environment.

The objective of our study is to test several probing behavioral hypotheses to identify the most fruitful manual palpation strategies to localize hard nodules in a soft tissue. Based on the relevant literature and simulation studies, we test three open hypotheses, which are formulated in the next section based on the simulation results. To the best of our knowledge, this is the first paper that establishes force-velocity modulation characteristics of manual palpation to detect hard nodules in soft tissues.

The rest of the paper is organized as follows. In Section II, finite element (FE) simulations are presented. Section III discusses the methodology of experimental studies on manual palpation. Then, in Section IV the experimental results and data analysis on manual palpation is described. Section V concludes the paper.

II. Finite Element Simulations

A. Design of FE Simulations

Previous clinical studies on manual soft-tissue examination behaviors for different organs, [19], [20] suggest that patterns of movement of fingers do matter in the effectiveness of identifying hard nodules in soft tissue. However, there is no fundamental evidence of the temporal modulation patterns of movement variables. To understand the possible influence of variable palpation behavior on the process of localization of hard nodules, FE simulations are carried out. This method can help to understand stress responses sensed from soft tissue during tactile examination. The result of manual palpation – the detection rate of hard nodules – depends on the magnitude of stress in the contact area. The higher force for the unit area is sensed, the more stress is induced in that area. Therefore, the results presented in this section might be used to explain the behavioral patterns of manual palpation.

The process of unidirectional one finger manual palpation over a silicone block was simulated in FE environment. The modulations of finger exerted force and velocity were changed during simulations.

FE simulations were conducted in ABAQUS 6.10. The silicone phantom was modeled based on the studies in [24] – a non-linear, isotropic, incompressible, and hyperelastic Arruda–Boyce model was used. The size of the model of the silicone block was set 50 × 50 × 30 mm^3. The element size of the mesh of the FE model was 1 mm, using a quadrilateral element type. The diameter of the embedded spherical nodule was set to 10 mm. The fingertip contact was modeled as a discretely rigid sphere with 20 mm diameter. The contact between the soft tissue and the indenting body was modeled as frictionless, assuming a perfectly lubricated surface. At the beginning of all simulations, the soft tissue was indented at 3 mm.

B. Results of FE Simulations

To understand the possible combination of force-velocity modulations during palpation, four types of palpation behaviors above the hard nodule were simulated: a) decreasing velocity and decreasing force, b) increasing velocity for the decreased force; c) constant velocity and decreased force, and d) no modulation in force and velocity – both variables are constant.

For the demonstration purposes, Fig. 1 shows the FE simulations with the deformation for the contact point above the nodule (decreasing velocity and decreasing force).

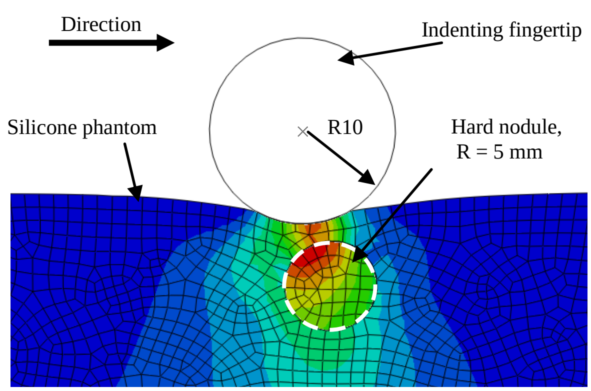

Fig. 1. FE simulation of stress in the silicone phantom indented with a fingertip (diameter 20 mm) above the nodule location (diameter 10 mm) for the location above the nodule

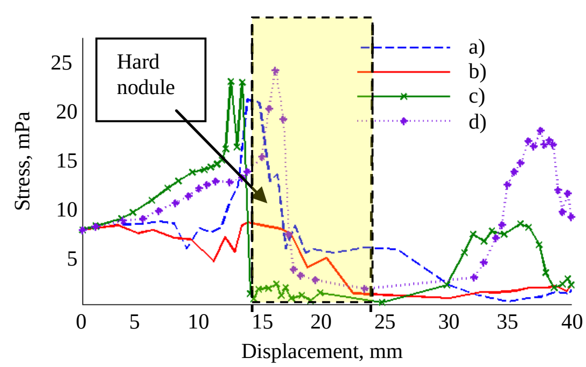

Fig. 2. FE simulation of stress for different palpation strategies: a) increased velocity and decreased load; b) decreased velocity and decreased load; c) constant velocity and decreased load; d) constant velocity and load

The results of the simulations, where the hard nodule is embedded 2 mm form the surface, are shown in Fig. 2. One can observe that applied force-velocity modulations are causing different stress responses in the area around the hard nodule. The decrease of stress magnitude can be observed after the nodule is touched. The response from the simulations c) and d) shows some peaks not only in the area of the nodule but also after it has been detected. While this peak is not observed for the strategies a) and b). For the decreased velocity strategy (b) the stress distribution is relatively uniform and less intense. The result of simulation with increasing velocity strategy (a) shows one high peak before the nodule.

It is possible to conclude that palpation behavior (i.e. applied force and velocity) can lead to different tactile feeling of a hard formation. Therefore, we can formulate three hypotheses about the characteristics of manual palpation: 1) during manual palpation, people apply certain strategies to detect hard formations in soft tissue; 2) the palpation speed influences the correct localization of an embedded hard nodule; 3) the localization and detection rate of nodules can vary depending on the palpation force and velocity.

III. Methodology of Manual Palpation

A. *Palpation Studies*

In order to test the hypotheses established based on simulation studies in section II, two sets of palpation tests involving silicone phantom were carried out within the framework of this study to understand the characteristics of manual palpation to localize hard nodules. First, manual palpation strategies to detect hard embodiments within the silicone phantoms were studied. The impact of the velocity of a subject's finger traversing over the tissue surface was recorded and examined during the second test. This work was approved by the King's College London Biomedical Sciences, Dentistry, Medicine and Natural & Mathematical Sciences Research Ethics Subcommittee. A total of twenty subjects participated in this experimental studies. In the study group, ten of the participants were experts in palpation techniques with at least five years surgical experience, while the remainders were considered novices with regards to soft-tissue palpation. The relation of stiffness between soft and hard silicone is fabricated to correspond to the stiffness ratio between healthy soft tissue material and tumors [22]. Therefore, for the creation of the phantom tissue, silicone gel RTV6166 (Techsil Limited, UK) with mixture ratio 4:6 and 900 mPa·s viscosity was employed. To simulate artificial tumors, silicone nodules were embedded in the phantom tissue. Hard silicone rubber compound RTV615 (Techsil Limited, UK) with mixture ratio 10:1 was used to fabricate hard spherical nodules with 4000 mPa·s viscosity. Two palpation tests are described hereafter:

1) *Test 1: To Understand Strategies to Detect Hard Embodiments*

This test is designed to analyze the strategies, evaluating velocity, trajectory and palpation force, which humans apply to detect hard inclusions. The subjects were first asked to apply "free" palpation, i.e. to palpate a phantom tissue with one finger in a not prescribed and unconstraint way with the aim to detect embedded nodules. One finger palpation is used in order to be comparable with the artificial palpation approach involving a single probe during RMIS. The silicone phantom (130×85×30 mm^3), Fig. 3a, contained four nodules of different diameters – 15, 12, 9 and 6 mm, all embedded 9 mm from the surface. During the second part of this test, subjects were asked to palpate a silicone phantom block (100×100×30 mm^3) in a linear unidirectional way in order to sense three hard inclusions, 10 mm in diameter, along a pre-defined path (Fig. 3b). Each subject performed five trials. Hard nodules were embedded 30 mm apart at different depths from the surface: 2 mm, 6 mm and 11 mm.

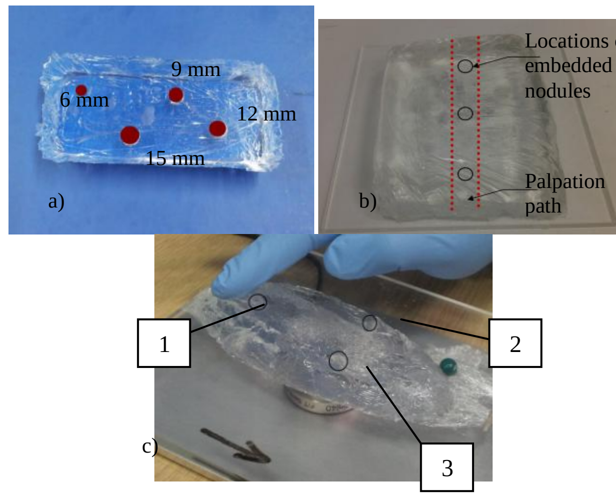

Fig. 3. Phantom tissue with the locations of embedded hard nodules for the palpation tests: a) sample for free palpation, b) sample for unidirectional palpation with marked palpation path, and c) Silicone phantom sample for Test 2, embedded nodules are marked (1, 2, 3)

2) *Test 2: To Understand the Impact of Traversing Velocity*

This set of experimental studies was designed to evaluate the impact of the velocity of the subject's finger during palpation on the detection rate of hard nodules. Subjects were asked first to localize embedded nodules during three sets of experiments applying unidirectional palpation across the surface of a silicone phantom. This was followed by three sets of experiments where unidirectional palpation was applied to an ex-vivo porcine kidney. Hard nodules 9 mm in diameter were embedded at different depths from the surface – 1 mm, 3 mm and 5 mm (Fig. 3c). The principle difference of each experimental set was the applied palpation velocity – slow, natural and fast. Natural palpation velocity is defined as the speed of palpation which feels most comfortable to the subject. Consequently, slow and fast traversing velocities were defined as velocities that are lower and higher than the natural velocity, respectively. The range of velocity magnitude is different for each subject, and is discerned during an analysis session, Section III (*B*). One of the aims of this study was to evaluate how the velocity range varies across trials and across subjects.

B. *Experimental Setup*

The experimental arrangement (Fig. 4) was designed to record the finger pressure, trajectory and velocity, thus, allowing the recording of the main characteristics of the finger movement. The force values of the applied pressure were measured with a force/torque sensor (Mini 40, ATI industrial automation), which is a 6 DOF sensor with a force sensing range of ±10 N in X and Y direction, ±30 N in Z direction and ±0.5 Nm for torque readings; normal force resolution is 0.01 N. The sensor is mounted under a transparent base plate, supporting the examined target material (i.e. the silicone phantom or the animal organ).

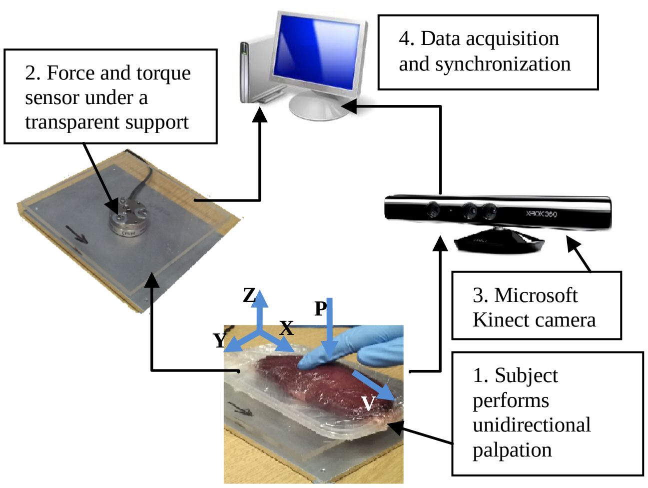

Fig. 4. Schematic arrangement of an experimental setup: The subject is performing palpation with one finger (1) – the main palpation features are: applied pressure *P*, velocity *V* and trajectory in three-dimensional space *XYZ*; the applied force is measured using a force/torque sensor, mounted under the transparent support plate (2) and the trajectory is measured by a three-dimensional vision system (3). All acquired sensor data is synchronized and processed

A three-dimensional vision system (Microsoft Kinect camera) was used to record the trajectory of the movement. It is equipped with a depth sensor and a video camera (640 × 480 pixel resolution, image acquisition 30 fps). The OpenCV package for Microsoft Visual C++ was used to track the three-dimensional movements of a subject's hand while performing palpation. Spatial position readings were recorded and used to obtain the magnitude of the finger velocity. To check the measurement accuracy of the camera, evaluation tests were carried out. The value of position accuracy depends on the velocity of the moving object – finger. Therefore the mean velocity of palpation, used during experimental studies was applied. The mean velocity magnitude was obtained from the manual palpation experimental data for fast palpation velocity and is shown in Section III (*B*).

Firstly, the hand position was recorded with the Kinect-based system, using a hand-tracking algorithm. Concurrently, the trajectory of the hand was recorded using stereovision (two separate cameras), and the position was obtained from a colored marker on the finger using Computer Vision Toolbox in MATLAB software. First two-dimensional position of the marker was obtained from each camera separately; then three-dimensional position of the finger was reconstructed. Comparing the obtained three-dimensional values from Kinect sensor and stereovision, the position accuracy for the Kinect camera is 1-2 mm.

C. *Data Analysis*

Data processing and statistical analysis are conducted using MATLAB 7.12.0 and R statistics i386 2.15.2 software packages. In order to smoothen noisy peaks from the positional data, a 2nd order low pass filter was used with cut-off frequency 0.2Hz and stop-band attenuation 16Hz. Three-way analysis of variance (ANOVA) and two-way t-test were used in order to analyze the interaction between various palpation factors and conditions on the detection rate of hard nodules and to observe the sources of variations, where appropriate. The impact of a factor was considered significant, if the null hypothesis was rejected with a 95% confidence level, for $p < 0.05$.

IV. Assessment of Palpation Techniques

A. *To Understand Strategies to Detect Hard Embodiments*

1) *Free Palpation*

As part of our analysis, we are very interested in establishing whether there was a correlation between the palpation variables during hard nodule localization, based on the palpation studies carried out in Tests 1. To understand the mechanisms and behaviors used by subjects and get the explicit information about the properties of the embedded nodule, we examined the experiments on "free" (unconstraint) one-finger palpation. Fig. 5 demonstrates the distribution of palpation velocity and applied finger pressure over the phantom organ. Naturally, palpation parameters are variable and are based on the decision of the subject. However, one can notice dependencies between applied force and velocity, as well as a certain type of behavior applied to the tissue at locations above the nodules. However, it is not possible to draw evident conclusions, based just on the representation of the parameters' magnitudes.

To observe the cross-modulations of applied pressure and velocity, we decided to investigate the local extrema values of each measurement (force and velocity) and the associated concurrent values of the other measurement (velocity and force). Local extrema values in this case are considered local maxima and local minima of force or velocity magnitude, and are found using a second derivative test. Fig. 6 shows the distribution of force and velocity for the local maxima and minima of the other measurement. The presented data are separately normalized with regards to the maximum value of each variable. A general trend is for velocities to increase in response to higher forces being applied. The velocity magnitude (Fig. 6a) does not vary significantly for maximum and minimum force. In addition, according to the two-way t-test there is no significant difference between velocity for local minima and that for local maxima of force pressure (p = 0.07). However, the force values, corresponding to extrema values of velocity (Fig. 6b) belong to two different distributions ($p < 0.05$). The force magnitude tends to decrease for higher velocity, but with a large deviation. These observations demonstrate that to explore a soft environment and to locate some hard inclusions in an efficient way one applies variable examination behavior. However, to understand the characteristics of manual palpation one needs to examine the modulations of force and velocity above the nodules.

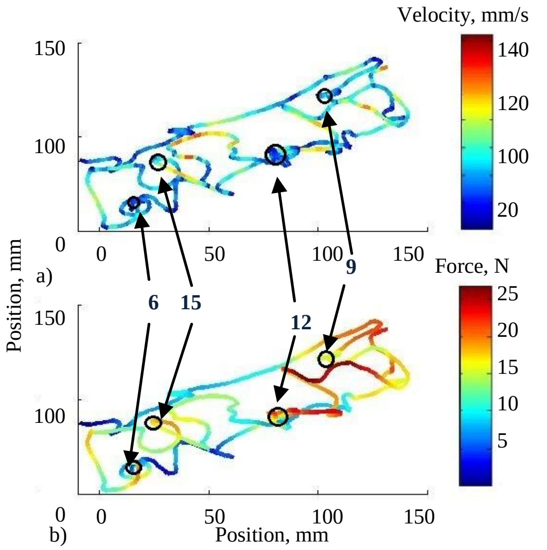

Fig. 5 Representative example of palpation path over a phantom tissue with four embedded nodules (diameters in mm marked with arrows): a) modulation of velocity magnitude, b) modulation of applied finger pressure.

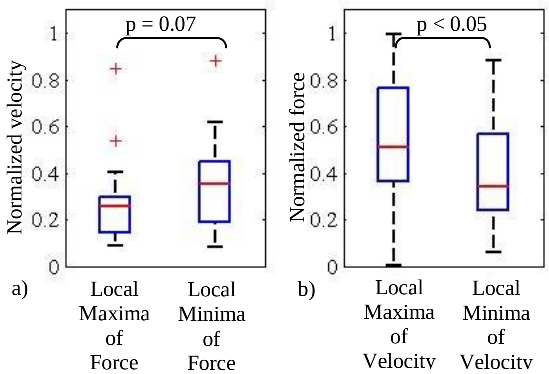

Fig. 6 Distributions of a) normalised force magnitude and b) normalised force magnitude; Y axis shows the local minima (1) and local maxima (2) peaks of force and velocity measurements, respectively.

2) *Unidirectional Palpation*

In order to further understand, what kind of behavior is used particularly for nodule localization, the recordings of movements of the finger when positioned on the tissue surface above the nodules are investigated. During "free" palpation, subjects were encouraged and allowed to apply any desired palpation trajectory and use various patterns, such as those learnt and developed during their professional practice.

To measure the variability of applied force and velocity when the finger is above a hard nodule, subjects were asked to palpate the tissue in a unidirectional fashion (Fig. 3b). There were three nodules placed along the palpation path for this test. However, only the third nodule (2 mm deep from the surface) was sensed by all subjects. As we are interested to study the force and velocity modulations in the area of a detected hard nodule only, the measurements from the region of the third nodule were analyzed separately. To observe the modulations of palpation behavior, the area around the nodule was separated into five interval regions. Fig. 7 demonstrates the location of the regions in respect to the location of the third nodule and displays the trajectory of the palpation path for one selected subject.

Each region represents a palpation over a certain location around the nodule. The width of the region above nodule was defined as 10 mm (Region 3) and surrounding regions as 5 mm (1, 2, 4, and 5). Experimental evaluation of force and velocity for each region has shown that the variance of each variable does not exceed 5 %. Unidirectional palpation path allows arranging the regions sequentially, without circular pattern, which would be more appropriate if the trajectory was following a curve or any random palpation movement around a nodule.

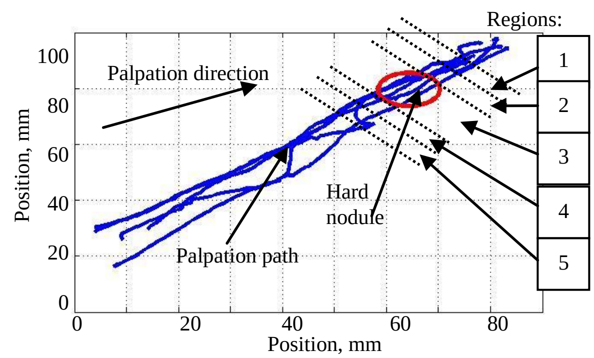

Fig. 7. The trajectory of palpation path – several trials of one selected subject; area of interest around the third nodule is shown with five interval regions (1-5).

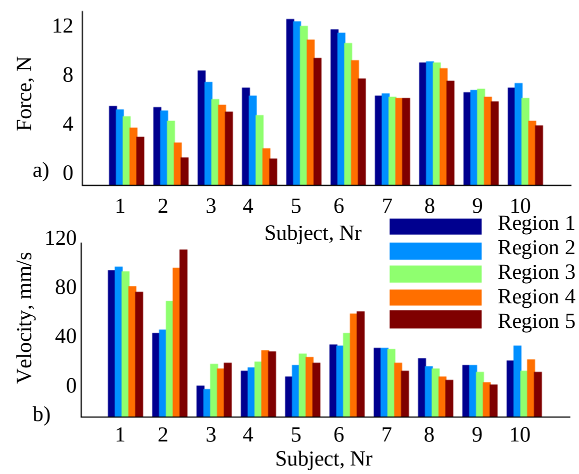

Fig. 8. Force (a) and velocity (b) distribution trends across ten selected subjects

Fig. 8 shows the mean force and velocity applied by ten selected subjects. Data for each subject is represented from Region 1 to Region 5.

To identify the possible trends in force and velocity modulation, the effects of force and velocity magnitude on the particular location (region) in the area around the nodule, and the influence of each individual subject were tested with the help of three-way ANOVA tests. The result showed that the pressure applied by the finger ($F_{(3.94)} = 7.92$, $p < 0.00001$) depends on the distance between the finger tip and the location of the hard inclusion. The effect of velocity and the impact from each individual was not significant ($F_{(3.94)} = 0.37$, $p = 0.55$ for force measurements and $F_{(3.94)} = 0.02$, $p = 0.9$ for the influence of each subject). These results show that the modulation of finger pressure is consistent for all trials, when the finger is in the vicinity of a detected nodule. However, the insignificance of the velocity magnitude in this context may suggest that the modulation of velocity changes differently among individuals due to some difference in their palpation behaviour. Alternatively, the modulation of velocity may not heavily contribute to sensing a nodule.

To check the presence of different behaviors of palpation, a first-degree polynomial was fitted to the normalized mean values of force and velocity for each region (1 – 5), and the slope (gradient) of the polynomial fit of the force was plotted versus the slope of the corresponding velocity polynomial, Fig. 9.

Two distinctive strategies were observed. It appears that 50 % of subjects have decreased both finger pressure and velocity while conducting an examination in the vicinity of the nodule. 30% of subjects have increased the velocity magnitude while at the same time decreased the applied force. In addition, there were 20% of subjects, who did not vary velocity and force significantly. The group of experts participated in the studies performed on the same level as other subjects showing similar behaviors.

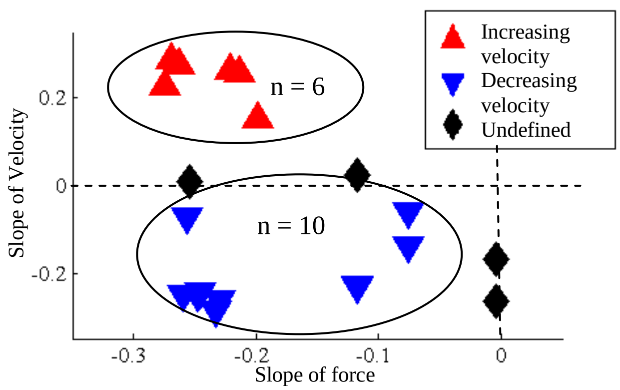

Fig. 9. Slope of force versus slope of velocity for subjects: two distinctive strategies can be identified – increasing and decreasing velocity. Outlier results are classified as “undefined strategy”.

To validate the statistical significance separately for both behaviors with different variation of velocity, a three-way ANOVA test was conducted again for two separate strategies, i.e. increasing velocity with decreasing force and decreasing velocity with decreasing force. The impact of both finger velocity ($F_{(4.00)} = 9.16$, $p < 0.0001$) and finger force ($F_{(4.0)} = 4.83$, $p < 0.01$) in the vicinity of a nodule were significant for the strategy with decreasing velocity. Similar observations can be made for the strategy, where the velocity increases: the impact of both velocity and force are significant for locations near the nodule ($F_{(4.17)} = 4.59$, $p < 0.01$) and ($F_{(4.17)} = 4.36$, $p < 0.01$). Thus, one can see that during a soft tissue examination and hard nodule probing, the finger palpation properties can be varied in two different ways. In particular, the subject either increases or decreases the finger velocity while, at the same time, reducing the applied pressure.

B. To Understand Strategies to Detect Hard Embodiments

In order to get a better understanding of the impact of the finger velocity on the detection of hard nodules, additional studies were carried out. Fig. 10 shows the summarized data for Test 2 and presents the influence of separate factors, such as subject, palpation medium and traversing velocity, on the detection rate of hard nodules. A three-way ANOVA test was carried out, to evaluate the importance of each separate palpation component and its influence on the detection rate. To compensate for the bias, a weighting was applied on the detection rate of hard nodules for all sets of experiments for all subjects. The weight was calculated from the best performance of each subject with no false positives. We found that the type of palpation medium had a significant effect on the results ($F_{(3.99)} = 6.23$, $p < 0.0001$). While on the other hand, the subject ($F_{(3.99)} = 2.27$, $p = 0.14$) and the palpation velocity ($F_{(3.99)} = 0.61$, $p = 0.44$) did not influence the detection rate of hard nodules. Therefore, it is important to emphasize the significance of the correctly chosen palpation technique for a given environment and to analyze the process of soft tissue examination considering features of the target material.

To evaluate the impact of the traversing velocity for the given medium (here: the silicone phantom) a three-way ANOVA test was performed on the set of palpation cases. Firstly, we studied the group of subjects with low level of palpation experience. Three factors influencing the detection rate were considered – subject sequence number, applied pressure and the magnitude of palpation velocity. The velocity had a significant effect on the detection rate ($F_{(4.17)} = 3.14$, $p < 0.001$). While, the effects of both force and subject sequence number have shown virtually no effect - ($F_{(4.17)} = 0.61$, $p = 0.33$) and ($F_{(4.17)} = 1.01$, $p = 0.44$), respectively. Secondly, the same analysis was carried out for the group of experts. Similarly, the impact of velocity was significant ($F_{(4.24)} = 8.97$, $p < 0.00001$). In addition, experts have used finger pressure to detect hard nodules ($F_{(4.24)} = 16.67$, $p < 0.00001$). This result confirms the importance of correctly chosing the traversing velocity and applied force; as is clear from the results, the experts achieved a higher detection rate.

To understand how the magnitude of velocity influences the detection rate of hard nodules, the analysis of different velocity magnitudes is carried out. Test 2 required to perform three trials using fast, natural and slow palpation velocities. The magnitudes of velocity were defined by the participants, based on their personal preference. Therefore, the values of the chosen palpation velocities for different subjects for the same trial (for instance, for natural velocity) are not the same. Thus, velocity data, which was defined experimentally, was devided into three groups, based on their magnitude. For this purpose, k-means clustering was used. The data for experts and novices was processed spearately. The results of the velocity distribution of both participant groups for three clusters are presented in Fig. 11. Compared with the experimentally defined velocities, there was 100%, 50%, and 61% correlation for the group of novices and 75%, 38%, and 55% correlation for the group of experts with sets of fast, natural and slow magnitudes of velocities.

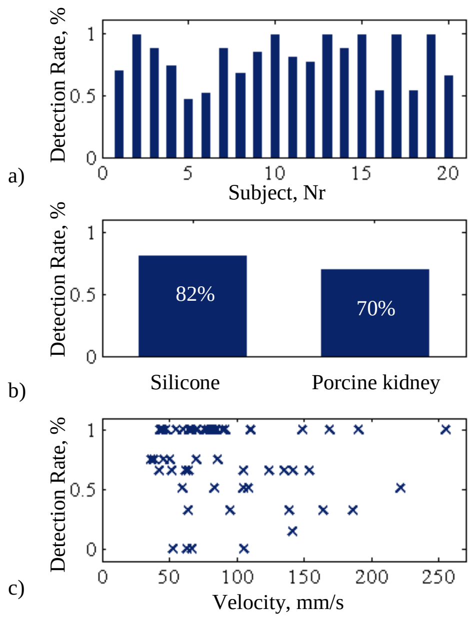

Fig. 10 Summary of hard nodule detection rate for a) different subjects, b) silicone and porcine kidney, c) velocity.

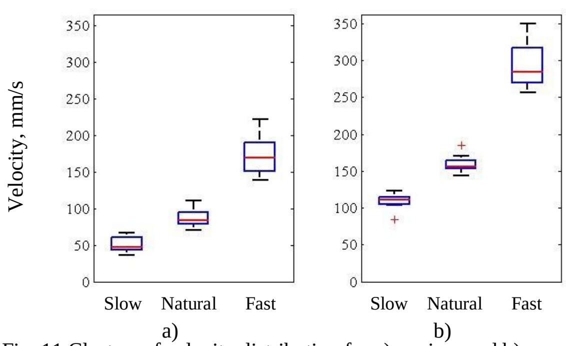

Fig. 11 Clusters of velocity distribution for a) novices and b) experts.

TABLE I
THE IMPACT OF PALPATION VELOCITY

Cluster	Experience	Detection Rate %	Velocity Magnitude mm/s	Detection Rate for Experimental Velocity Distribution %
Slow	Novice	87	36 - 67	96
Natural	Novice	83	70 – 110	83
Fast	Novice	69	139 – 222	68
Slow	Expert	96	85 - 123	89
Natural	Expert	82	144 - 220	89
Fast	Expert	53	256 – 350	74

To evaluate the impact of the velocity magnitude, the detection rate for each cluster for each group was calculated, Table I. It can be observed, that the velocity magnitude applied by the group of experts is higher. However, the results for the detection rate for each set of velocity are similar. These results demonstrate the importance of the correctly chosen velocity magnitude. According to the data, the highest detection rate of nodules for the silicone phantom is observed for slow palpation velocity.

V. Conclusions and Discussion

In this work we test three hypotheses to understand the characteristics of manual palpation to localize hard nodules in soft tissues: 1) certain manual palpation strategies are applied to detect hard formations in soft tissue; 2) the speed of palpation influences the detection rate of hard nodules; 3) force – velocity modulations during manual palpation influences the localization and detection rate of hard nodules. Thus, to get a better understanding of how the process of tactile probing during robotic surgery should be implemented, the manual palpation has been studied.

Ten out of twenty participants in our studies had at least five years experience in manual palpation. Therefore, it is natural to expect that the exploration trajectory of their movement should follow some certain pattern. For instance, during first part of Test 1, the majority of subjects have indicated that in order to locate a hard nodule and understand its shape, they have applied circular movements around suspicious area. Such types of palpation, we can call them high level techniques, are very useful to apply during manual soft tissue examination, as for a person it is easier to implement them. However, the objective of this study is to provide a basis to design optimal robotic behaviors during soft tissue examination to localize hard formations. Thus, we examine low level aspects of manual palpation, such as finger exerted pressure and palpation velocity.

In this work we try to understand the main characteristics of manual palpation to detect of hard nodules, with the help of palpation studies involving human participants. The developed experimental equipment allowed recording forces applied by subjects during palpation, as well as to follow the dynamics of the movement. By conducting several tests on manual palpation, together with FE simulations, the strategies used to detect hard nodules during unidirectional palpation are examined. Therefore, based on the experimental evidence, we conclude that the first hypothesis is valid. Consequently, force - velocity modulations are applied differently for the detected palpation strategies. The correct combination of palpation variables for the given examination environment may lead to higher detection rate of formations. This supports our third hypothesis outlined in this paper.

The presented work explores, with the help of the experimental studies and statistical evaluation the influence of the palpation velocity on the detection rate of hard formations. It was shown that the application of the appropriate palpation velocity increases the performance. The results of Test 2 show that during palpation experts use both applied force and velocity to locate hard formations, while for novices just the variability of velocity significantly influences the detection rate. However, the detection rate for novices and experts does not differ significantly. This might happen because novice subjects intuitively are applying more suitable palpation velocity, as shown in Fig. 11. Therefore, the second hypothesis holds more validity for the subjects with no palpation experience.

To sum up, the detection and localization of stiffer abnormalities in soft tissues is influenced not only by the parameters of the probe, but also by applied palpation strategy – the correct choice of force and velocity components for the given environment. The interaction dynamics of the finger or a probe during palpation is the result of the applied force – velocity modulations on viscoelastic parameters of soft tissue. In addition, the work presented in this paper can be a valuable source of information to develop behavioral guidelines for soft tissue examination during RMIS, as well as the design insights for new probing devices.

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